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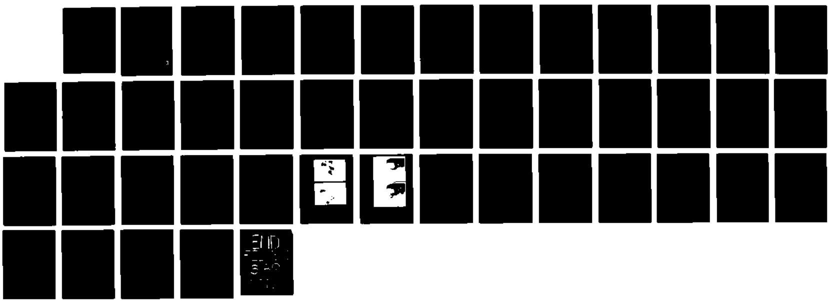

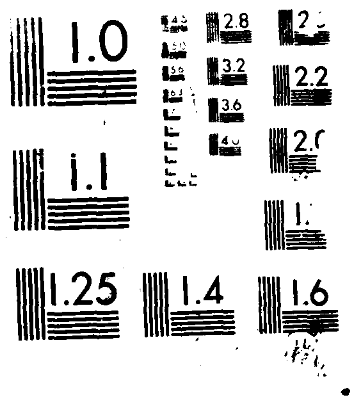
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Efficient Dealiasing of Doppler Velocities Using Local Environmental Constraints

Michael D. Ellis and
Steven D. Smith

NOAA, Environmental Research Laboratories
National Severe Storms Laboratory
Norman, OK 73069

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16. Abstract

A Doppler velocity dealiasing algorithm is described that processes one radial at a time by comparing that radial with a previous radial. This technique has worked reliably on numerous Doppler radar data sets for clear air, thunderstorm, and severe thunderstorm situations. It was also tested on four volume scans from severe weather environments with difficult aliasing problems to determine statistically how well the algorithm performs in a worst case environment. Of some 1.2 million velocities in these severe storms, 0.2% were improperly dealiased, and 93% of those were above 13 km height in the storm-top divergent region where shears were extreme. Every tornado, mesocyclone, gust front, microburst, and storm-top divergent signature was preserved, and could be identified by automated algorithms. This algorithm is adaptive and therefore efficient because simple checks are made initially, and progressively more sophisticated and time-consuming checks are used only if they are needed.

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PREFACE

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Efficient Dealiasing of Doppler Velocities Using Local Environment Constraints

Michael D. Eilts and Steven D. Smith[1]
NOAA, Environmental Research Laboratories
National Severe Storms Laboratory
Norman, Oklahoma 73069

January 1989

1. INTRODUCTION

Both range and velocity ambiguities are inherent limitations of Doppler weather radars. The equation relating these ambiguities is:

$$RV_n = c\lambda/8$$

where R is the unambiguous range, V_n is the unambiguous velocity (Nyquist velocity), c is the speed of light, and λ is the radar wavelength (Doviak and Zrnić, 1984). Radial velocities that fall outside the range of $\pm V_n$ (called the velocity aliasing interval) are aliased into the range $\pm V_n$. Thus the measured radial velocity, V_m, is related to the true velocity by $V = V_m + 2nV_n$ where the integer n specifies the aliasing interval. It is the purpose of velocity dealiasing techniques to determine the proper n for each measured radial velocity.

The NEXt generation weather RADar (NEXRAD) and Terminal Doppler Weather Radar (TDWR) programs rely heavily on automated algorithms to detect certain meteorological phenomena. These algorithms require that Doppler velocities are properly

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[1] Presently with UNISYS Corporation, Trevose, PA

dealiased, thus it is of paramount importance to employ a velocity dealiasing scheme that is reliable and can run in real-time.

This paper details a Doppler velocity dealiasing technique called the Local Environment Dealiasing (LED) scheme, that was developed by the authors at the National Severe Storms Laboratory. It has been tested using Doppler radar data from both severe and non-severe storm environments. The data has contained Nyquist velocities from 20 to 35 m s^{-1} and range gate spacing from 120 m to 250 m with no noticeable change in performance caused by these different radar parameters. A strong point of this algorithm is that it uses a simple velocity-to-velocity comparison when shears and aliasing problems are small (~99% of the time), but uses more sophisticated techniques when shears are strong and more difficult aliasing problems arise.

2. REVIEW OF DEALIASING TECHNIQUES

Since the late 1970's several software methods have been developed to dealias Doppler velocities. The simplest approach to velocity dealiasing is to apply radial continuity constraints along individual radials. The velocity at each range gate is compared with the preceding velocity, and is adjusted by an integer number of aliases until their difference is less than the Nyquist velocity. This approach is very sensitive to noise, i.e., a single velocity in error can cause the rest of the radial to be dealiased improperly.

Ray and Ziegler (1977) developed a more robust technique that requires the radially sampled velocities to be normally distributed about their mean velocity. The proper aliasing interval can be determined by requiring a non-normally distributed sample of velocities to be corrected so that a normal distribution is achieved. This method is difficult to apply in cases where severe aliasing causes a large spread of velocities and biases the sample mean.

Bargen and Brown (1980) developed another single radial method. Their technique also assumes continuity along radials and compares individual velocity values with an average of preceding values. The proper aliasing interval of the datum is then determined by minimizing the difference between its value and the average. This type of dealiasing scheme fails in noisy areas and areas of strong shears. Bargen and Brown also use operator interaction to help dealias velocity fields with difficult aliasing problems. In this paper we do not address manual or interactive systems since they would place excessive demands on the human operator in the operational environment of NEXRAD or TDWR.

Merritt (1984) proposed a potentially more powerful approach which utilized data in two dimensions, i.e., data from a complete revolution of the radar at one elevation angle. This technique is essentially a three-step method. The first step segments the data into regions of similar velocities where all the velocities in each region are within some percentage of the Nyquist velocity

of each other. Then the shears along the borders are minimized by determining the proper aliasing interval for each region. The third step uses a wind model to determine the proper aliasing interval of large areas, which should already be internally consistent. The basic method developed by Merritt has been enhanced by both Boren et al. (1986) and Bergen and Albers (1988).

Boren et al. (1986) added a wind field model monitor to the Merritt system by using a simple set of rules to determine if the wind field model is correct. If errors occur, the current model is abandoned and replaced with a preceding model that was considered valid. This eliminates propagation of errors that might occur in the wind field model, which was found to be an intermittent problem with the Merritt system. Bergen and Albers (1988) have also modified the Merritt technique by adding a noise filter, a technique to deal with ground clutter, and the use of a sounding (rather than a wind field model) to estimate the aliasing interval of distant echoes which do not have continuous velocity measurements out to their range.

The biggest disadvantage of the Merritt technique and its derivatives is the amount of computer time that the algorithm takes to dealias radial velocities. The Bergen and Albers version of the algorithm takes 20-30 seconds on a VAX 8800 computer to dealias a velocity field containing 360 radials by 512 range gates. Another apparent failure mode of the algorithm is a "bridging" problem in areas of strong shears (such as in

regions of tornadoes). In areas of strong shears, aliased data is sometimes incorrectly grouped in a region with data that is not aliased, causing incorrect dealiasing. Most of these bridging problems have been resolved by employing a second pass through the data, but at the expense of another 10 seconds of computer time (Albers, private communication).

3. THE LOCAL ENVIRONMENT DEALIASING TECHNIQUE

The LED algorithm uses two-dimensional continuity to dealias velocities. However, the dealiasing is done along radials, processing one radial at a time by comparing it with the previous dealiased radial. Thus, it uses little memory and potentially could be placed in a preprocessor to dealias radials "on-the-fly" for real-time operations. This technique will be described below. A simplified flow chart of the algorithm is shown in Fig. 1 and more detailed flow charts are shown in Appendix A.

Before the data are dealiased, velocities are set to a missing flag if the corresponding spectrum width is high (> 2/3 the Nyquist velocity) or the signal-to-noise ratio is low (< 0 dB). The remaining data is considered valid although ambiguities and noise may still exist.

Initially, a velocity is subjected to a radial continuity check by comparing it with the spatially closest (within five range gates) preceding valid velocity along the same radial. If the velocities are within a radial continuity threshold of each other (e.g., 15 m s^{-1}), then the velocity is retained, error

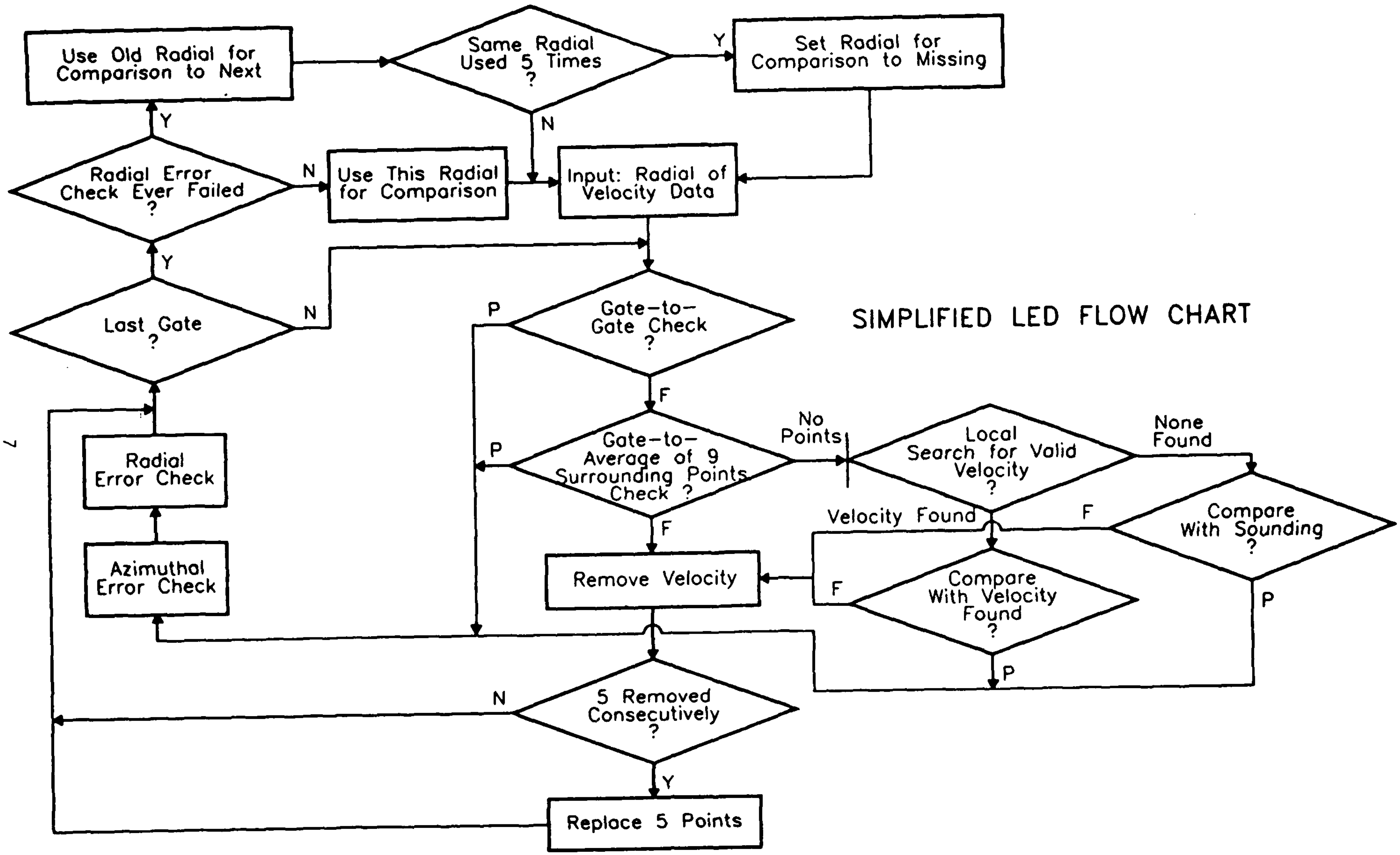


Figure 1. Flow chart diagram of the LED algorithm.

checks are made (error checks will be discussed in Section 3a), and the algorithm precedes with the next velocity in the radial. Likewise, if the current velocity is not within the threshold of the previous velocity, but can be dealiased into that domain, it is dealiased, some error checks are made, and the algorithm examines the next velocity in the radial. The threshold value used in this first comparison is varied depending on the type of shears and velocities expected. For severe thunderstorm environments a value of 15 m s^{-1} has been found to work well when Nyquist velocities are in the range of 20-35 ms^{-1}, while for general thunderstorm and clear air environments, a value of 5-10 m s^{-1} is favored. In an operational mode where no threshold changes are possible, a value of 15 ms^{-1}, or a similar percentage of the Nyquist velocity should be used. The main affect that using a larger threshold will have is to reduce the editing function of the algorithm such that very few points will be determined to be noise and removed.

If the initial radial continuity check fails then an average of nine neighboring points--four in the same radial (closer to the radar) and five in the adjacent preceding radial (adjacent point and four further from the radar) is computed as illustrated in Fig. 2. In this way an average of only previously edited and dealiased velocities is computed for comparison. This average is intended to give approximately even weight to data both azimuthally and in range, i.e., data from ranges closer and farther from the radar and from both azimuths are used. If a value in

aliased

-19	-17
-24	-20
-23	+17
-22	+18
-19	+18
-20	+19
- 5	+ 2
- 1	0
0	- 3
+ 3	+ 4
+ 3	+ 3

range ↑

azimuth →

dealiased

-19	-17
-24	-20
-23	-23
-22	-22
-19	-22
-20	-21
- 5	+ 2
- 1	0
0	- 3
+ 3	+ 4
+ 3	+ 3

range ↑

azimuth →

Figure 2. Sample of two radials of velocity data with current velocity circled. The boxed-in area is the velocities that are averaged to compare to the current velocity if the gate-to-gate velocity check fails. This datum has a Nyquist velocity of 20 m s^{-1}, thus the current velocity could be either +19 or -21, Neither of these values are within a threshold of 10 m s^{-1} of the preceding velocity value. However, the average of the nine surrounding points is -11.8 and -21 would be correctly chosen as the value of the current velocity. This shows the utility of an average using both radials.

question falls within an adaptive threshold of this average it is kept as is, some error checks are made and the algorithm goes to

the next velocity in the radial. This adaptive threshold is the larger of 15 m s^{-1}, 40% of the average, or two times the standard deviation of the nine points. Thus in areas of noisy data, strong shears, or strong velocities, a larger threshold is used. If the velocity in question can be dealiased to fall within this adaptive threshold of the average, then it is dealiased, some error checks are made, and the algorithm precedes with the next velocity along the radial. If the velocity value is not within this domain, or cannot be dealiased into this domain, then it is deleted from further processing.

If no points are found to compute the average (near edges of storms or at singular points) then the algorithm looks back (towards the radar) in the same radial ~5 km (30 gates, an adaptable threshold) and then forward ~2.5 km (15 gates) in the previous radial to find the first valid velocity. If a valid velocity is found and the velocity in question is within a threshold (1.5 times the radial continuity threshold) of this value (or can be dealiased) then it is kept as is (or dealiased), some error checks are made and the algorithm precedes with the next velocity along the radial.

If no points are found for comparison, it is possible to use sounding or Velocity Azimuth Display (VAD) (Browning, 1969) wind information to try to place the velocity in question in the proper aliasing interval. More discussion on this subject is given in Section 4.

a. Error Checks

There are two types of error checks incorporated into the LED algorithm. These checks are done during the same pass through the radial so that efficiency is optimized.

The first is simply a check to make sure that too many consecutive points have not been removed. If five consecutive points are removed by the algorithm, these points are replaced by initially comparing the first point removed with the preceding velocity in the same radial using a larger threshold (1.5 times the earlier radial continuity threshold). If this comparison fails, then the first point removed is compared to an average of 15 velocities in the previous radial. If this first point is within the relaxed threshold of this average (or can be dealiased into the same domain) it is left unaltered (or dealiased). If this value is not (or cannot be dealiased) within the threshold of the average, then it is kept in the zeroeth aliasing interval (i.e., left unaltered). The other four points that had previously been removed are then replaced by comparing them with a running average of the other point(s) that have been replaced.

The second type of error checks are ones that determine whether the edited and dealiased velocities in the two radials are consistent with assumed meteorological limits of shear. The first check is an azimuthal shear check. If the difference between two azimuthally adjacent velocities is greater than a threshold (1.2 times the Nyquist velocity) and 17 (a variable number which is equivalent to 2.5 km in range) azimuth pairs in a

row meet this criteria, then it is determined that the present radial has been incorrectly dealiased. These last two thresholds were set empirically, based on the largest Tornadic Vortex Signature (TVS) observed in Oklahoma, thus TVS's and other small-scale circulations should be retained but unrealistic shears that extend over longer ranges are deemed erroneous. If the radial is determined to be dealiased incorrectly, the last (17th) velocity is placed in the aliasing interval closest to the velocity in the previous radial. The velocity data are then re-examined using a least-squares-minimizing technique, moving down the radial (towards the radar) until it is determined that no errors exist. This least-squares-minimizing technique is simply a comparison of the current velocity with the nearest valid velocity in the preceding radial and the nearest valid velocity farther from the radar in the same radial. The aliasing interval of the current velocity is chosen by minimizing the square of the differences between the current velocity and these neighbors. If, while working down the radial, the current velocity is ever kept in the same aliasing interval as the algorithm placed it earlier, then the minimizing technique is terminated, and errors in the radial are considered corrected.

A final gate-to-gate check is made to see if there are any unrealistic discontinuities (greater than the smaller of 1.7 times the Nyquist velocity or 45 ms^{-1}) anywhere along the radial. If an unrealistic jump is found, the algorithm assumes that an error has been made, and the radial of data is not used for

dealiasing the velocities in subsequent radials; instead the previous radial is used again. This is allowed to occur up to four times before the system is reinitialized, causing a radial to be dealiased with no previous radial with which to compare. This ensures that if an error has occurred it will not propagate and affect more than four adjacent radials.

If two gate-to-gate unrealistic discontinuities occur in the same radial and they are of the opposite sense, an aliasing interval is added (or subtracted) to all of the velocities in the gates between the two jumps so that no unrealistic jumps remain. If no unrealistic jumps remain in the radial after this correction, the radial will be used for comparison with the next radial.

4. DETERMINING THE PROPER ALIASING INTERVAL FOR DISTANT STORMS

Distant storms that are far enough from the radar so that no clear air returns can be detected out to them create a unique problem. Because there is no continous data between the radar and the storm there is no information as to which aliasing interval the velocity from the first gates with appreciable signal should be placed. Since the algorithm virtually assures internal consistency and bases the proper aliasing interval for the whole continuous area on the first few gates and radials that intersect the storm, it is important to determine the proper aliasing interval for these locations.

Presently, the LED algorithm uses a wind sounding if no local data is found to compare a velocity value with. Data from the sounding level which is closest to the height of the radar data are used to compute the radial component of the wind. If the Doppler velocity value is within 1.5 times the radial continuity threshold of the sounding component, or can be dealiased to fall within that domain, then the velocity data are kept (or dealiased) and the algorithm proceeds. If the velocity value is not kept, or cannot be dealiased, then it is removed. If five points are removed consecutively via sounding comparison, the deleted data are handled the way that other groups of removed data are handled.

The use of environmental wind soundings to help dealias velocities was first suggested by Hennington (1981). Supporting evidence that a sounding will represent flow in a storm was given by Zrnić et al. (1986). They removed velocities where reflectivities were very high (> 40 dBZ) and computed a wind estimate with the remaining velocities in storms. When comparing these wind estimates with soundings taken near the time of the storm, there was good agreement. It is believed that data on storm edges generally compare sufficiently well with sounding information collected near the time of the storms. When running a dealiasing algorithm in real-time, the sounding should be updated frequently (e.g., every hour) so that it represents the current flow in the atmosphere.

Since sounding information is collected only twice a day by the National Weather Service and flow in the atmosphere may change considerably between soundings, the sounding should be updated using either radar wind information or possibly profiler data after it becomes available. Doppler weather radar Velocity Azimuth Display (VAD) wind information (Browning and Wexler, 1968) will often only be available in the lowest two kilometers of the atmosphere, but this is where the largest changes tend to occur.

Two other techniques may also be used to estimate winds with height using radar data. These are the Volume Velocity Processing (VVP) and the Sectorized Uniform Wind (SUW) techniques (Doviak and Zrnić, 1984). The SUW technique allowed Zrnić et al. (1986) to estimate wind soundings up to 15 km height using storm data. The only requirement is that the storm data subtend at least a 30° arc from the radar. The VVP technique assumes a linear wind in a volume (30° azimuth x 1-2° elevation x 20-30 km range) and could also be used to estimate wind soundings in clear air or storms. Data from rawinsondes and radar will have to be merged to determine a representative composite sounding.

There will be times where a sounding will not represent flow in the entire area of Doppler radar coverage. An example of this is when a strong gust front or cold front approaches the radar from one direction at low levels. Generally it may be difficult to determine the proper aliasing interval of these phenomena if the first gates in each radial are aliased (which should not

happen very often). If this is the case, motion of this feature may be needed to determine the proper aliasing interval, e.g., if motion of a feature is toward the radar and a high percentage of the velocities are positive, then it is probable that the area is aliased.

5. ALGORITHM TESTING AND STATISTICAL RESULTS

The LED algorithm has been tested on numerous data sets which have included some very difficult dealiasing problems due to radar artifacts (e.g., ground clutter) and strong azimuthal and radial shears. Some, in fact, had shears that spanned a complete aliasing interval (49 m s^{-1}) range gate-to-range gate along a radial and a TVS had azimuthal shears as high as 80 m s^{-1} between two adjacent radials. In general, the algorithm performed reliably in TVS regions and areas of severe radial and azimuthal shear failing only when Nyquist velocities were too small to resolve the shears (i.e., Nyquist velocities of < 30 m s^{-1} in severe storm environments). In order to properly dealias a high percentage (> 99.5%) of radial velocities, a Nyquist velocity of > 20 m s^{-1} is needed for most situations; however, a Nyquist velocity of > 30 m s^{-1} is needed for severe thunderstorm environments.

a. Testing of the LED Scheme on Severe Velocity Dealiasing Problems

The LED algorithm was used as a front end to the TDWR gust front algorithm (Witt and Smith, 1987) and was tested on 320 low-elevation angle 360° scans which were collected in the Denver area. Visual review of the output using hard copy color plots of the radial velocity fields, revealed no dealiasing problems involving more than 10 contiguous points (all of these confined to noise regions) were found in the analysis sample of ~3.5 million velocity values. A similar version of the LED algorithm has also been used extensively in a research environment to dealias velocity data collected in severe storms, microbursts, gust fronts, and clear air. Thus, the utility and accuracy of this algorithm in dealiasing radial velocities in typical clear air, storm, and severe thunderstorm situations has been shown. Since it is of paramount importance that a velocity dealiasing algorithm works during times of severe weather (which is also the time of the most severe aliasing problems, i.e., the time that most dealiasing algorithms fail), four extreme cases of severe weather and accompanying aliasing problems were chosen to test the LED algorithm. The reader should remember that results in non-severe weather will be much better than the results from this severe-aliasing test.

The four cases chosen for this test are listed in Table 1. For each of these cases a full tilt sequence (sector scans from

Table 1. Cases used for testing of the LED scheme and the severe weather and aliasing problems associated with the data.

Date/Time(CST)	V_n(ms^{-1})	Severe Weather/Aliasing Problems
22 May 1981/1909	34.2	One mile wide tornado that was rated F4 on the Fujita scale. Extreme TVS shears (azimuthally and radially) at low to mid-levels and similar storm-top-divergent shears.
26 May 1985/2038	28.5	Baseball size hail reported. Two strongly divergent storm tops with colliding outflows whose convergent velocity difference gate-to-gate was >50 m s^{-1}.
27 May 1982/1927	24.5	Gust front that had measured winds of 50 ms^{-1}. Gust front shear at the leading edge had discontinuities nearly a full aliasing interval gate-to-gate.
02 May 1979/1646	34.2	Orienta(F2) and Lahoma(F4) tornadoes. TVS and storm-top-divergent shears.

0° elevation angle taken incrementally up to storm top) nearest the time of maximum severity of the storms was used. In each of these tilt sequences there were radials that had a velocity discontinuity nearly equal to the aliasing interval gate-to-gate because there were no obvious jumps in the measured radial velocities, yet, using neighboring radials it was obvious that there was a strong shear zone. Doppler radial velocities can sometimes be truly ambiguous, and sometimes only a subjective choice of the location of the shear zone is possible. If areas such as this occur in the data, no dealiasing algorithm (or trained human observer) will be able to resolve the proper aliasing interval for all velocities. It is desired that the LED scheme (when such ambiguities occur) make a best guess at the velocity field, but the scheme should not allow errors due to ambiguities to propagate.

The LED algorithm was run on four tilt sequences of data; the time, date, and type of weather occurring are shown in Table 1. The LED dealiased velocities were compared with "truth" which was determined by the authors' subjectively in consultation with other meteorologists. The threshold values given in Table 2 were set the same for all of the data sets. Representative soundings with only two levels were used to help dealias distant storms. Measured error rates of the algorithm for these severe storms are given in Table 3. For these four extreme cases of aliasing, 0.2% (2392/1,219,675) of the velocities were improperly dealiased (Table 3). Of these, 1563 were at the 8° elevation

Table 2. Thresholds used for testing the four severe cases.

Threshold	Value
Low signal-to-noise ratio	0 dB
High spectrum width	2/3 V_n
Velocity range gate-to-range gate comparison	15 m s^{-1}
Velocity range gate-to-average comparison	15 m s^{-1}
Radial extent of largest allowable TVS shear	17 gates (2.5 km)
Strength of gate-to-gate velocity discontinuity to be called unrealistic	smaller of 45 m s^{-1} or 1.7 V_n
Velocity-to-sounding comparison	22.5 m s^{-1}
Velocity-to-local search for data	22.5 m s^{-1}

Table 3. LED algorithm error statistics.

Date	Time (CST)	Total # Velocities	Number Aliased	# Improperly Dealiased	#Improperly Dealiased Below 13 km
5/22/81	1909	392,403	68,592	477 (0.12%)	111
5/02/79	1646	64,855	897	8 (0.18%)	8
5/27/82	1927	297,675	30,161	344 (0.12%)	52
5/26/85	2038	464,675	26,510	1,563 (0.34%)	0
TOTAL		1,219,675	68,592	2,392 (0.20%)	171

angle (height of 14 km AGL) of the 26 May 1985 storm where an entire divergent region was improperly placed one aliasing interval too high. However, this should not cause harmful effects on pattern recognition-based algorithms since the magnitude of the divergence was unaffected. In fact, if the data

from this elevation angle alone were given to a human analyst he would likely conclude that the proper aliasing interval for the divergent region was the same as the one chosen by the LED algorithm. Only by examining other elevation scans can one determine the proper aliasing interval for the velocities in question.

Almost all of the improperly dealiased velocities in these four severe storms were in the storm top divergence regions where velocities and shears were the strongest. Of the 2392 improperly dealiased velocities 2221 of them (93%) were at heights > 13 km, the bulk of which were in three areas. The first area, mentioned before, contained the 1500 velocities from May 26, 1985.

The other two were areas in which the edge of strong shear zones were not detected by the LED algorithm because they had excessive discontinuities gate-to-gate almost equal to the aliasing interval. Thus these areas were placed in the wrong aliasing interval until the radial shears fell to detectable levels. In all three of the larger areas of improper dealiasing it would be very difficult for a human analyst to determine the actual location of the shear zone without some corroborating evidence.

Of the 171 velocities that were improperly dealiased at heights lower than 13 km, ~75% of them were caused by, or were located on, the first radial that intersected a storm and thus the algorithm had no data from a preceding radial to use in the

dealiasing procedure. These errors did not propagate more than two radials into the storm and were confined to less than 20 gates in range. The remaining velocities that were improperly dealiased were scattered groups of three to five velocities which were located near strong shear zones (either real or induced by noise). **Every tornadic vortex signature, every mesocyclone signature, every gust front signature, and every storm top divergence signature, no matter how severe, was maintained as an identifiable signature which could be detected by an algorithm.**

b. Statistics

Since this algorithm relies heavily on input/output operations to read each radial and write it out, it is not very useful to show how long it takes for the algorithm to run since these input/output operations are very time-consuming. Instead, we have chosen to examine the percentage of the time certain parts of the algorithm are used, to show that the LED algorithm essentially acts as a sophisticated gate-to-gate velocity dealiasing algorithm. It thus should run quickly and efficiently enough to be used in real-time. The speed of this algorithm also relies heavily on the input data since the more difficult it is to dealias, the more checks and comparisons are made. The test of the algorithm on these four demanding data sets shows the percentage of times that each part of the algorithm is used in a severe storm environment. In an operational, real-time mode the simple gate-to-gate velocity check will be all that is needed a

higher percentage of time than represented here. Table 4 shows how often each of seven parts of the algorithm were used for the four tilt sequences tested here. It is interesting to note that ~99% of the time the simple gate-to-gate check was enough to determine the proper aliasing interval for the velocity in question. Another 0.7% of the velocities were placed in the proper aliasing interval by comparing to an average of surrounding points. A local search, if no points were found to average, yielded another 0.07% and finally 0.17% of the points are compared to a sounding to try to resolve which aliasing interval in which the velocity should reside. During these checks, 0.3% of the velocities are determined to be noise and are removed, and subsequently 25% of those are replaced because too many were removed consecutively.

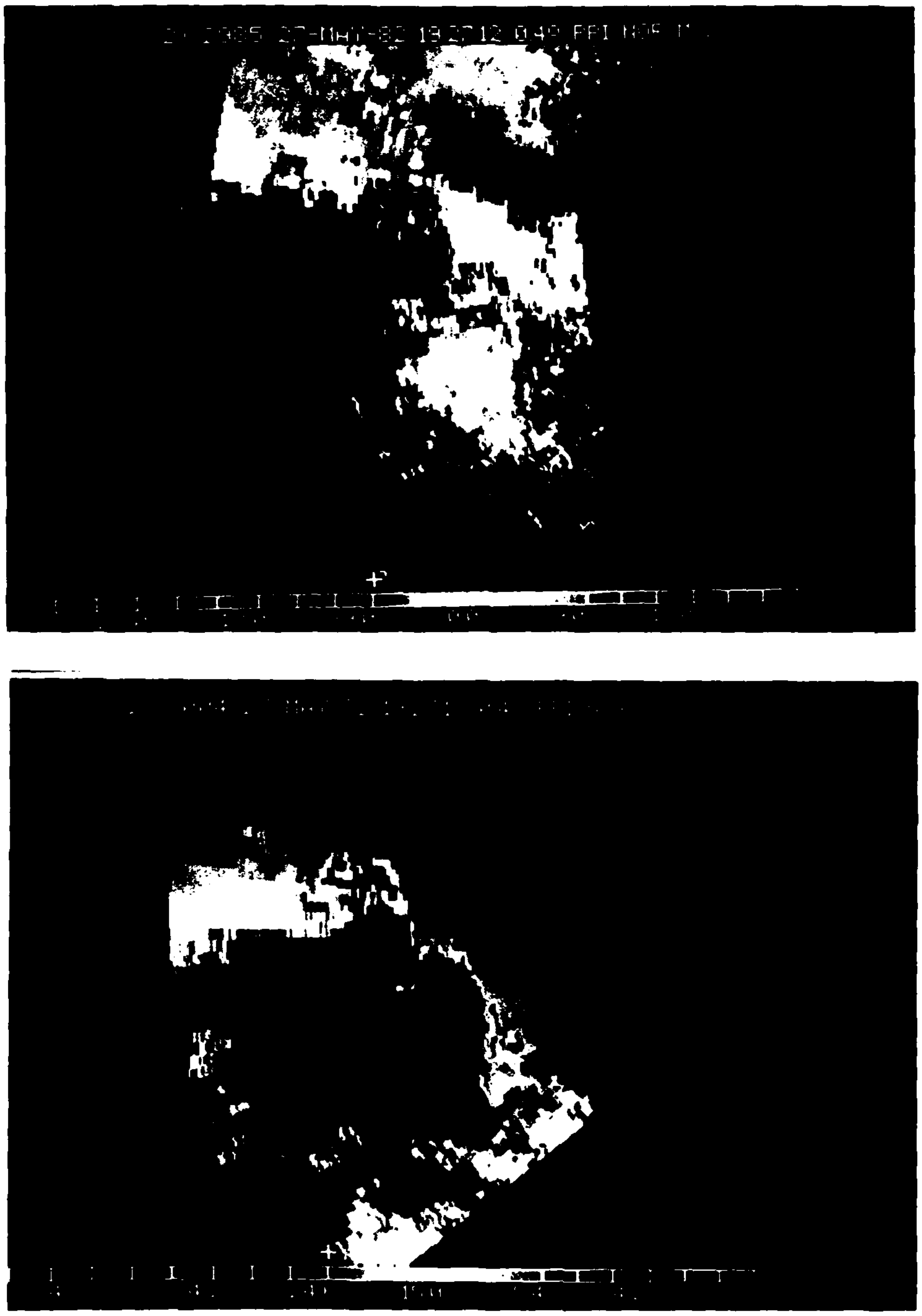
The azimuthal error check causes the least-squares-minimizing technique to be used on 1.9% of the radials. Thus, even though 99% of the velocity values are dealiased by a simple gate-to-gate check, it is the other 1% which typically give dealiasing algorithms problems. It is also of interest to note that the 1% of data, if not handled correctly, can cause a much larger percentage of the data to be erroneously dealiased due to the propagation of errors. LED resolves these problems using more sophisticated methods. The result is an algorithm which runs quickly but yet can dealias very difficult radial velocity fields.

Table 4. Number of, and percentage of times that individual parts of the LED algorithms were used during testing on the four severe storm cases.

	5/02/79	5/22/81	5/26/85	5/27/82	Total
Total gates:	64,855	392,403	464,675	297,742	1,219,675
# velocities (%) dealiased by gate-to-gate check	63,835 (98.6%)	387,225 (98.6%)	460,228 (99.0%)	295,258 (99.2%)	1,206,546 (98.9%)
Local search for gates	138 (0.21%)	309 (0.08%)	217 (0.047%)	220 (0.074%)	884 (0.072%)
Used sounding	93 (0.14%)	795 (0.20%)	717 (0.15%)	445 (0.15%)	2,050 (0.17%)
Compare with average of 9 surrounding pts.	639 (0.98%)	3,019 (0.77%)	3,164 (0.68%)	1,575 (0.53%)	8,397 (0.69%)
Velocity removed	178 (0.27%)	1,716 (0.44%)	1,066 (0.23%)	691 (0.23%)	3,641 (0.30%)
Velocity replaced	30	380	285	305	1,000
# of radials least-squares-minimizing technique was used	2 0.35%)	55 (3.1%)	22 (1.3%)	17 (1.6%)	96 (1.9%)
Total # of radials	564	1,747	1,734	1,036	5,081

c. Examples of Results

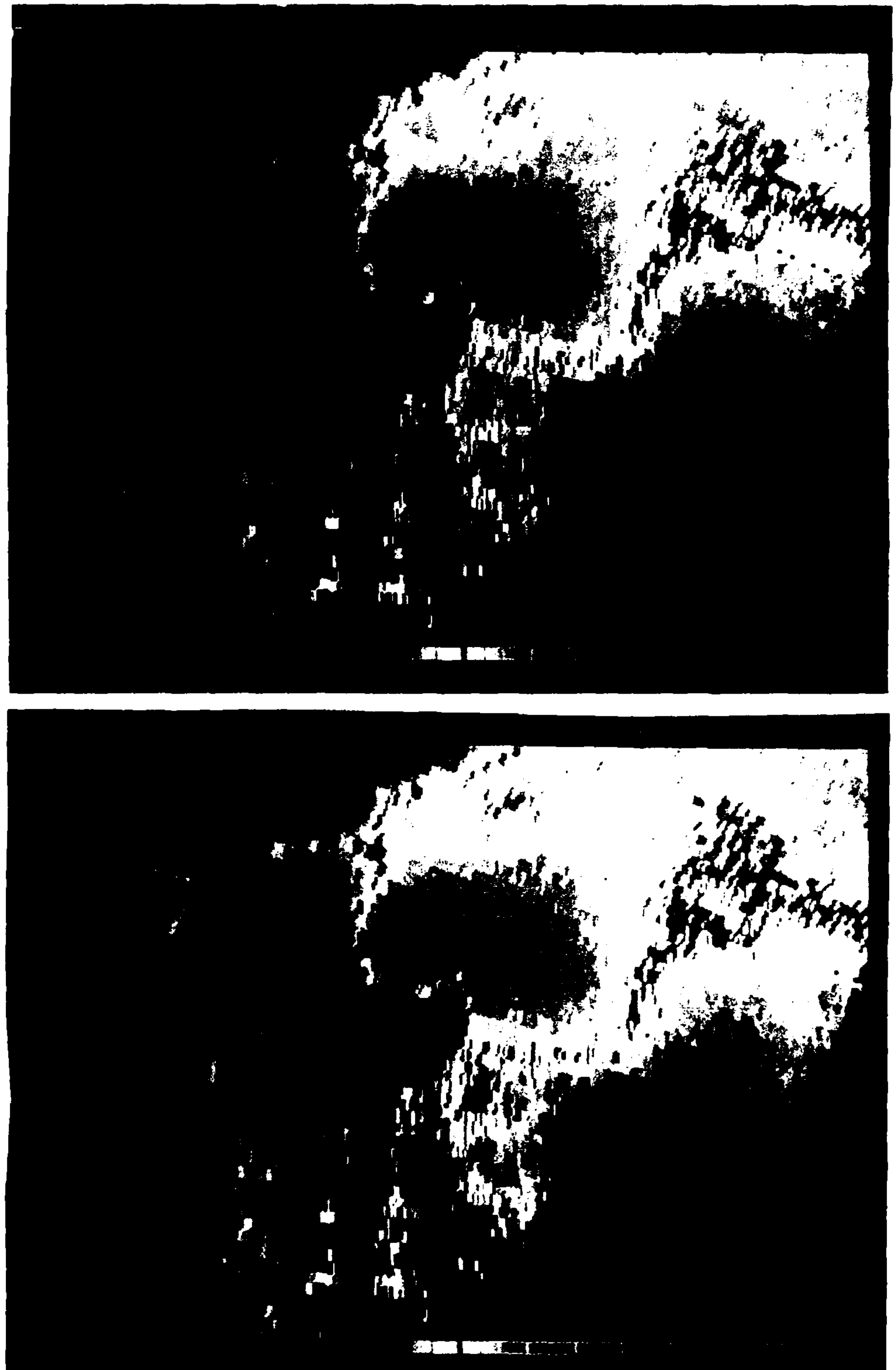
Figures 3 and 4 are examples of aliased and LED algorithm dealiased radial velocity fields for two of the four cases tested here. The radial velocity field shown in Fig. 3 was collected on 27 May 1982 during a severe gust front which had extreme shear at the leading edge (gate-to-gate discontinuities near the aliasing interval of 49 m s^{-1}). The LED algorithm handled this case very



a) aliased

b) dealiased

Figure 3. Doppler radial velocities color coded by the scale at the bottom. Positive radial velocities are away from the radar, and negative are towards. a) is the aliased velocities; b) is the LED algorithm dealiased velocities. The radial velocity field is the 27 May 1982, 1927 CST, 0.4° elevation angle scan. This data was collected during a severe gust front that propagated towards the radar from the southwest. Notice that the velocity scale has been changed in b) to better show the strength of the gust front.



a) aliased

b) dealiased

Figure 4. Doppler radial velocities color coded by the scale at the bottom. Positive radial velocities are away from the radar, and negative are towards the radar. The radial velocity field is the 2.6° elevation angle data collected during the time of the Binger, Oklahoma tornado on 22 May 1981 at 1910 CST. a) is the aliased velocities; b) is the LED algorithm dealiased velocities.

well except for a few velocities on the northern edge of the bow echo where azimuthal shears were also near the aliasing interval between adjacent radials. The gust front is identifiable as a strongly convergent shear feature.

The Tornadic Vortex Signature in Fig. 4 (characterized by strong positive and negative velocities azimuthally adjacent to each other) is that of the Binger, Oklahoma tornado of 22 May 1981. The aliased velocities in this radial velocity field are nearly all properly dealiased by the LED algorithm and the TVS is properly portrayed.

6. REAL-TIME VELOCITY DEALIASING CONSIDERATIONS

The LED algorithm described above was used as a front end to the gust front/wind shift algorithm during the real-time 1988 TDWR Operational Test and Evaluation (Hess et al., 1988). During the OT&E no known gust front/wind shift algorithm errors were caused by improper dealiasing of the radial velocities, whereas in previous years, numerous errors were caused by improper dealiasing using a single radial dealiasing algorithm.

Both the NEXRAD (terminal NEXRAD) and TDWR radar systems, as well as other real-time Doppler radar systems, have the need for real-time velocity dealiasing. Doppler radars with a wavelength of 10 cm usually are operated with nyquist velocities between 20 and 35 ms^{-1}. However, TDWR systems will have a wavelength of 5 cm causing operational nyquist velocities to be in the range of 15-25 ms^{-1}. When nyquist velocities below 25 ms^{-1} are used for

data collection in a severe storm environment, there will be areas in which the proper aliasing interval of certain velocity values will not be able to be resolved due to high shears. Most of these high shear regions will be near the storm-top region of severe thunderstorms.

In a practical sense, the algorithms developed for use with the terminal NEXRAD and TDWR systems mainly use data from the low-elevation angle tilts where, in general, shears are weak enough to be resolved with nyquist velocities >20 m s^{-1}. Data collected in the vicinity of large tornadoes may be the only exception to this. Shears associated with microbursts and gust fronts will generally be weak enough to be resolved with nyquist velocities >20 ms^{-1}.

The LED algorithm detailed in the previous section should be able to properly dealias radial velocities as long as the nyquist velocity is large enough to resolve the strongest shears in the environment. In areas where the nyquist velocity is <u>not</u> large enough to resolve shears the algorithm will fail (as will any other), however, a number of error checks are made to insure that these errors will not propagate.

The LED algorithm has been tested using data with gate spacing between 120 and 250 m and Nyquist velocities between 20 and 35 m s^{-1} with no noticeable changes in performance caused by these changes in parameters. If Nyquist velocities less than 20 m s^{-1}, or gate spacing greater than 250 m will be used, then

further testing of the LED algorithm should be done to determine if any changes are necessary to accommodate these differences.

There is some concern that the removal of velocity values by the LED algorithm (values that are determined to be noise) may have some deleterious affect on algorithm detection of wind shear events, especially the microburst algorithm. However, it has been found that a radial continuity threshold of 15 ms^{-1} almost eliminates the removal of data in microburst and gust front environments.

7. CONCLUSIONS

The Local Environmental Dealiasing Algorithm discussed in this paper was initially developed for applications in a research mode at the National Severe Storms Laboratory. Within the last years it has been enhanced and made ready for real-time applications because it became apparent that there was a need for an efficient algorithm that could reliably dealias radial velocities. The LED algorithm was tested as part of the gust front algorithm in the 1988 TDWR Operational Test and Evaluation. No known gust front algorithm errors were caused by improper velocity dealiasing.

The LED algorithm's performance on severe aliasing problems was tested by running the algorithm on four tilt sequences of Doppler velocity data collected during severe storms. For these four extreme cases of aliasing, the algorithm properly dealiased 99.8% of the velocities. Ninety-three percent of the improperly

dealiased velocities were in the storm-top-divergent region of storms where shears were extreme. Every tornado signature, every mesocyclone signature, every gust front signature, and every storm-top-divergent signature--no matter how severe--was maintained as an identifiable signature which could be detected by an algorithm. During this test, 99% of the velocities were properly dealiased using only the range gate-to-range gate comparison; thus efficiency is optimized because sophisticated procedures which are more time-consuming are only used if they are needed.

Velocity dealiasing is an important process for both NEXRAD and TDWR because the performance of algorithms that incorporate radial velocity data depends heavily on properly dealiased velocities. The LED algorithm bridges the gap between highly-sophisticated, time-consuming, dealiasing schemes, and simple, efficient, but error-prone schemes. This algorithm is an adaptive one in that it uses simple, efficient checks first, and cascades to more time-consuming and sophisticated procedures only if they are needed; therefore, efficiency is optimized, while sophistication and accuracy are maintained.

Further research is necessary to determine the proper way to gather and update wind sounding information in a real-time operational mode so that distant storms are placed in the proper aliasing interval. It may be possible to use the wind field model and monitor developed by Merritt (1984) and Boren et al. (1986) or the technique developed by Bergen and Albers (1988) to help determine a representative sounding.

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APPENDIX A

Flow charts of four different segments of the LED algorithm our found on the next four pages. These flow charts detail a) the local search for velocities to compare with if no valid velocity values are found to compute a local environment average (Fig. A-1), b) the technique to replace five consecutive velocities that have been removed (Fig. A-2), c) the azimuthal error check and subsequent least-squares-minimizing technique (Fig. A-3), and d) the radial error check (Fig. A-4).

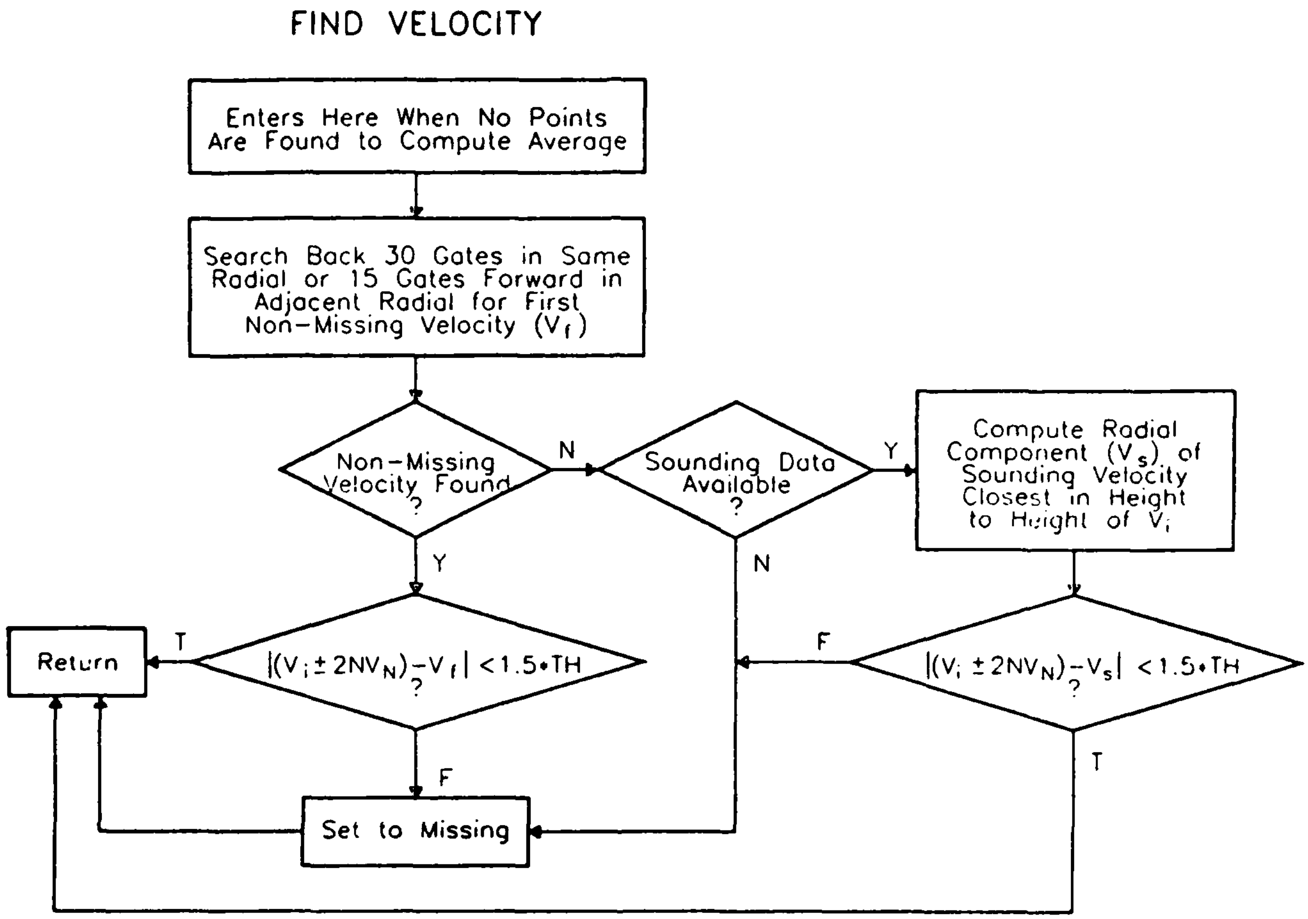

Figure A-1. Flow chart of the local search for a valid velocity to compare with when no valid velocities are found to compute a local environment average.

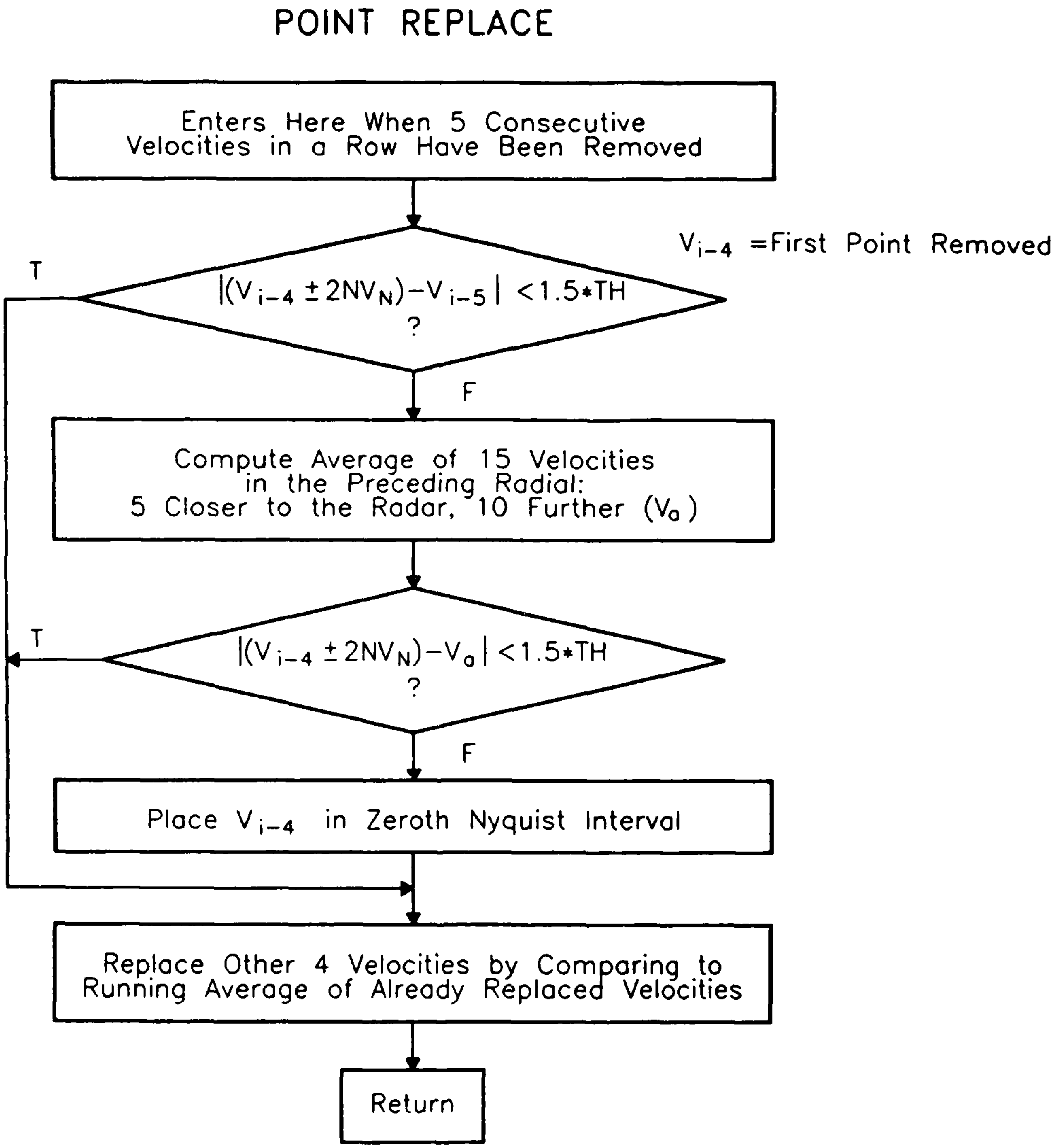

Figure A-2. Flow chart depicting the technique to replace five consecutive velocities that have been removed.

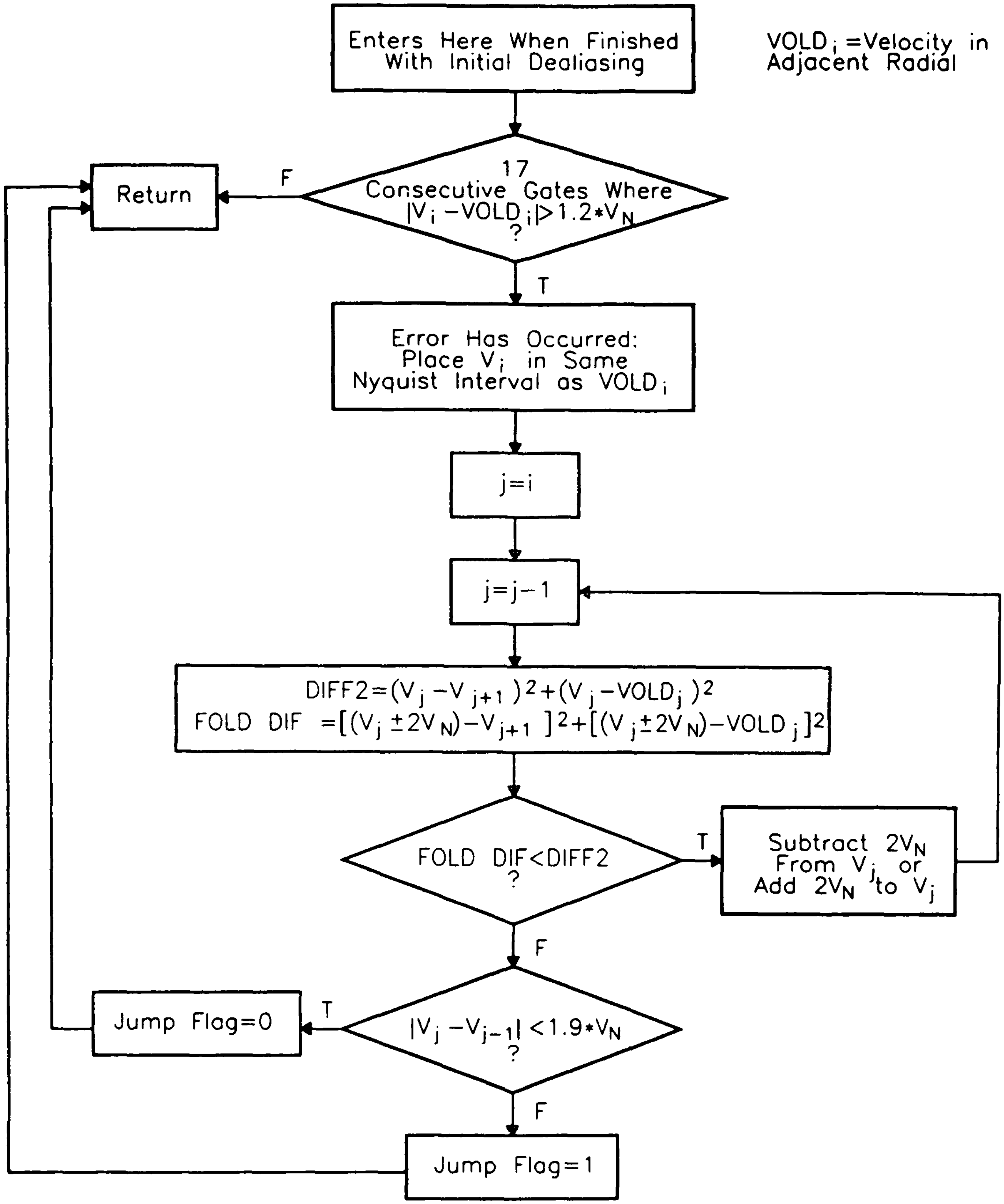

Figure A-3. Flow chart of the azimuthal error check and subsequent least-squares-minimizing technique.

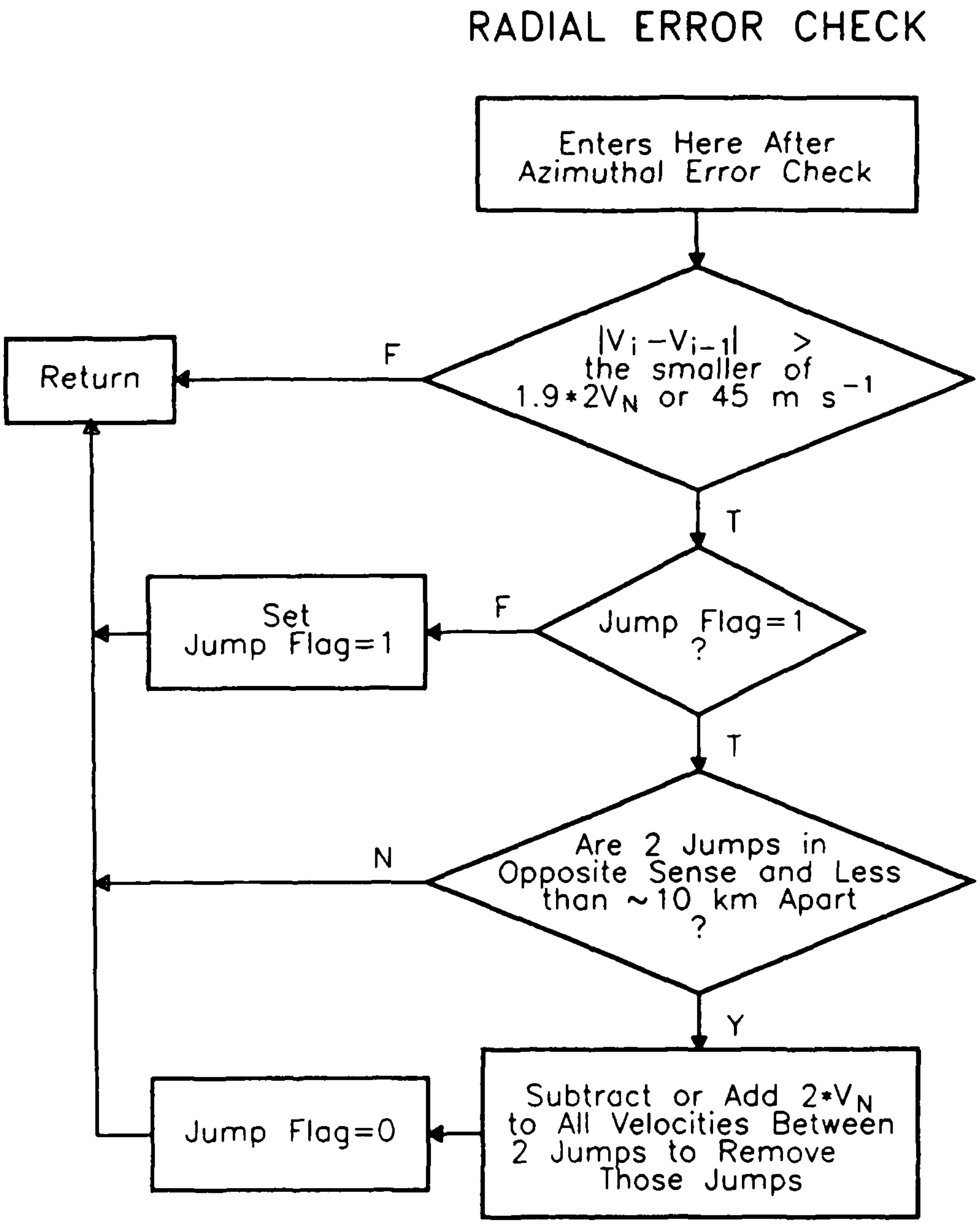

Figure A-4. Flow chart depicting the radial error check.

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